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Method and Circuit for Generating an Auxiliary Symbol for Adjusting a QAM Demodulator

This invention relates to a method and a circuit for generating an auxiliary symbol which serves to more quickly bring decision-feedback loops into lock when digital signals locked to a quadrature signal pair are received. Such loops are used, for example, for the adjustment of sampling instants, for the adjustment of an equalizer that removes linear distortion during the reception of the quadrature signal pair, or in an automatic gain control circuit to adapt the received signals to the dynamic range. The invention relates in particular to the operating state of the receiver in which the carrier and phase-locked loops of the local oscillator are not yet locked.

In encoded form, these digital signals, which are also referred to as "symbols", represent a one-digit or multidigit binary value. Encoding for transmission is accomplished via the quadrature signal pair, which corresponds to a vector that at given instants takes up discrete positions in the amplitude and phase space of

the quadrature signal pair. These instants follow each other at equal intervals and must be hit by the sampling clock pulses as precisely as possible. These transmission methods are known as "quadrature amplitude modulation" (QAM) and "phase-shift keying" (PSK).

In a conventional receiver for receiving digital signals, a complex multiplier or mixer, which is controlled by a local oscillator, downconverts the received QAM signal, which is modulated onto a carrier, to baseband. If digital signal processing is used, this downconversion can take place prior to or after A/D conversion (A/D = analog-to-digital), with the signal advantageously being sampled and digitized at the symbol rate or a multiple thereof. If the digitization rate is an even-numbered multiple of the symbol rate, each of the symbol clock pulses coincides exactly with a real sample value. The digitization rate is advantageously locked to the recovered symbol rate via a phase-locked loop (= PLL). If the digitization rate is free running in relation to the necessary symbol rate, the symbol is ultimately formed as time information via an all-digital sample-rate conversion. In this manner, a temporal interpolation between the digitized sample values of the digital signal is controlled. Automatic gain control circuits ensure that the respective dynamic range is fully utilized and that the received symbols are correctly mapped onto the symbol decision stage. An adaptive equalizer reduces intersymbol interference, which results from linear distortion caused by the transmitter, the transmission path, or the receiver.

In high-quality demodulators for QAM or PSK signals that are based on the prior art, the circuits for controlling the frequency and phase of the local oscillator, the automatic gain control, the symbol clock recovery, and the adaptive equalizer look at the differences between the received symbol and that element of the predetermined symbol alphabet which is regarded by a decision stage as the most probable. This type of control over the decision symbol is referred to as decision-feedback control. Since in prior-art digital demodulators the decision-feedback loops are coupled together, lock is difficult to achieve as long as the control for the carrier of the local oscillator, which downconverts the received signal to baseband, is not yet stable in frequency and phase. Frequently, the lock condition can only be achieved if the respective frequencies and phases are relatively close to their desired values. Examples of decision-feedback loops are found in a book by K. D. Kammeyer, "Nachrichtenübertragung", published by B. G. Teubner, Stuttgart, 2nd edition, 1996, pages 429 to 433, in Chapter 5.7.3, "Adaptiver Entzerrer mit quantisierter Rückführung", pages 200 to 202, in Chapter 5.8.3, "Entscheidungsrückgekoppelte Taktregelung", pages 213 to 215, and in Chapter 12.2.2, "Entscheidungsrückgekoppelte Trägerphasenregelung im Basisband", pages 429 to 431.

It is an object of the invention to provide an improved method and circuit which decouples decision-feedback loops in a digital-signal receiver from each other,

whereby rapid acquisition is made possible for the sampling clock, the equalizer, or the amplification regardless of the frequency and phase of the local oscillator.

According to the features of the independent claims 1 and 11, the object is attained essentially by making available, during the adjustment phase of the decision-feedback loops, an auxiliary symbol which replaces the decision symbol. For the formation and definition of the auxiliary symbol, the radius and angle information of the received signal or of the preliminary symbol is used. The error in the angle information due to the unknown frequency and phase deviation of the local oscillator is deliberately ignored. This is achieved by providing an auxiliary-symbol decision facility which, instead of assigning to the received signal an element from the predetermined symbol alphabet, generates an auxiliary symbol that lies on one of the possible nominal radii. "Nominal radii" as used herein means those radii on which in QAM the symbols of the alphabet lie in the plane determined by the quadrature signal pair. As the angle component of the auxiliary symbol, the angle information of the sampled digital signal is used. In polar coordinates, the auxiliary symbol thus corresponds to the vector intersection point of the sampled digital signal with the most probable nominal radius. The decision as to which nominal radius is the most probable is made via range limits which in the simplest case are determined by the possible radii of the respective QAM standard, namely by defining limit radii. These limit radii form annuli of

different widths in the quadrature signal plane which contain one nominal radius each. It is also possible for the range limits to be determined not only by the nominal radii but also by the positions of those elements in the quadrature signal plane which have to be taken into account. In that case, the range limits no longer define ideal annuli but more or less distort the latter. This means, however, that the respective angle information influences the auxiliary decision, but only with little weight. Furthermore, entire regions of the quadrature signal plane can be excluded from the auxiliary decision ("masked out") because their evaluation is too uncertain.

In a preceding step it is determined where the individual nominal radii and range limits lie, so that the most probable nominal radius can be selected. For the case where the decision is made via the most probable nominal radius through pure annuli, the radii limits are determined, which advantageously lie midway between two adjacent nominal radii. Whether the respective radii or range limits are retrieved from a table or whether they are continuously recalculated in accordance with the transmission standard is of secondary importance.

In higher-order QAM, some of these annuli may be so narrow that their evaluation in the presence of usual interference is uncertain. Since, on the other hand, their contribution to the control process is small, this uncertainty is hardly disturbing. The effect of such uncertain annuli can be further reduced by suitable weighting of the control information, or they are

completely masked out. Furthermore, annuli can be permitted which enclose the respective nominal radius more narrowly and thus cover it with greater certainty. If the measured radius lies outside these narrower radii limits, no auxiliary symbol will be formed, because this would be too uncertain.

For a received digital signal with the quadrature components $I = R \cos \alpha$ and $Q = R \sin \alpha$ that falls into an annulus of nominal radius Rsi, the auxiliary-symbol decision facility forms, at the position with the nominal radius Rsi and the angle α, an auxiliary symbol with the polar coordinates Rsi, α. In order that this auxiliary symbol can be used as a "decision symbol" by the decision-feedback loops of the clock recovery, gain control, or equalizer, its quadrature components $I_h = R_{si} \cos \alpha$ and $Q_h = R_{si} \sin \alpha$ are formed.

The radius R and the angle α are determined mathematically from the quadrature components I, Q:

$$R = \sqrt{(I^2 + Q^2)}$$

$$\alpha = \arctan(Q/I)$$

There are also resolvers which convert from Cartesian coordinates to polar coordinates in another manner. In the digital signal processing portion of such resolvers, the "Cordic" technique is usually employed, because it uses only binary additions and multiplications, which can be implemented by simple arithmetic shifts. Furthermore, other approximation methods or tables are possible. For the inverse conversion, too, i.e., for the conversion

from polar signal components R and α to their quadrature components $I=R \cos \alpha$ and $Q=R \sin \alpha$, a Cordic converter, a table, or an approximation method can be used.

The invention and advantageous developments will now be explained in more detail with reference to the accompanying drawings, in which:

Fig. 1 shows the positions of the 16 symbols in the I/Q quadrature plane for a 16-QAM signal;

Fig. 2 shows a Nyquist pulse with synchronized sampling;

Fig. 3 shows a Nyquist pulse with nonsynchronized sampling;

Fig. 4 shows the positions of 16 symbols of a 64-QAM signal in the first quadrant;

Fig. 5 is a block diagram of a first embodiment of a demodulator with an auxiliary-symbol generator in accordance with the invention; and

Fig. 6 is a block diagram of a second embodiment of a demodulator with an auxiliary-symbol generator in accordance with the invention.

In Fig. 1, a plane in which the positions of the 16 symbols $S_{s,m}$ of a 16-QAM signal are marked is determined by a quadrature signal pair I, Q. The designations of the individual symbols $S_{s,m}$ differ by the specifications of the respective Cartesian coordinates. The symbol $S_{-3,1}$, for example, has the value -3 as the I-coordinate and the value 1 as the Q-coordinate. The diagram also contains circles K_1, K_2, and K_3, on which the symbols $S_{m,n}$ are located. Associated with the circles are the radius values $R_1=1.41$, $R_2=3.16$, and $R_3=4.24$, which are calculated

starting from the origin. To define the symbols $S_{m,n}$ via their polar coordinates R, α, the respective angle components α are necessary; for the symbols $S_{3,1}$, $S_{3,3}/S_{1,1}$, and $S_{1,3}$, for example, the angles are α=18.3°, α=45°, and α=71.7°, respectively. The circles and associated radii on which the symbols $S_{m,n}$ are located according to the respective transmission standard will henceforth be referred to as nominal circles and nominal radii Rs, respectively. To simplify the notation, the index notation of the designations and reference characters will be abandoned.

Figs. 2 and 3 each show the signal s of a single Nyquist pulse sn. The continuous line represents the analog waveform of the digital signal, which is transmitted as a continuous signal. A typical feature of the Nyquist pulse sn is that the signal passes through zero at all symbol sampling instants t/T=+/-n (n=1, 2, 3...) and that it has a nonzero value, namely the actual symbol value S, only at the symbol sampling instant t/T=0. If the analog signal S or the Nyquist pulse sn is sampled and digitized at an integral multiple of and synchronously with the symbol sampling rate ts as shown in Fig. 2, exactly the sample value at the instant t/T=0 will provide the digital symbol state. The sample values between the symbol sampling instants t/T=+/-n, for instance at t/T=-0.5 or t/T=1.5, are insignificant for the symbol recognition and can be ignored.

Things are different if the Nyquist pulse sn is sampled and digitized as shown in Fig 3. Here the sampling and

digitization clock td is synchronized with the symbol sampling clock ts neither in frequency nor in phase. Hence, the sampling instants td for the digitization coincide with one of the regular symbol sampling instants t/T only accidentally if at all. Accordingly, reliable sensing of the digital symbol state at the instant t/T=0 by means of the existing sample values is not readily possible. Here, symbol sampling devices are necessary which perform a temporal interpolation of the real sample values to determine the sample value at the instant t/T=0 as precisely as possible. Because of the relatively narrow Nyquist pulse, which has first zero crossings at t/T=-1 and t/T=+1, it is advisable to use interpolation methods of higher order, so that the pulse peak S at t/T=0 will be reliably detected. The small round circles in Figs. 2 and 3 correspond to the real sample values. The small squares in Fig. 3 correspond to interpolated sample values, which are available as data for further processing. During the transmission of a digital data stream, the individual Nyquist pulses sn are combined and transmitted as I and Q components.

Fig. 4 shows in the I/Q plane the 16 positions of the symbols Sm,n of a 64-QAM signal in the first quadrant. For the acquisition process according to the invention it is irrelevant which quadrant the 64 elements Sm,n of the symbol alphabet are located in. In the case of symbol S7,7, the symbols S-7,7, S7,-7, and S7,-7 of the three other quadrants have been added in parentheses by way of illustration. The diagram of Fig. 4 shows for the individual symbols Sm,n the Cartesian coordinate grid

determined by the two quadrature signal components I, Q. The grid lines are defined by a scale from 0 to 8 on each of the two coordinate axes I, Q.

The diagram of Fig. 4 also contains nominal circular arcs Rs which belong to the first quadrant and pass exactly through the symbols Sm,n. For the 16 symbols in the first quadrant, and hence for all 64 symbols of the QAM signal, there are 9 nominal arcs Rs1 to Rs9, which are drawn as continuous lines. Associated with each nominal arc is a nominal radius Rsi, which is why in Fig. 4 the reference characters of the nominal radii Rs1 to Rs9 are used as reference characters for the nominal arcs. Three arcs intersect only one element Sm,n in the first quadrant. Arc Rs1 intersects symbol S1,1, arc Rs3 intersects symbol S2,2, and the outermost arc Rs9 intersects element S7,7. All other arcs intersect two symbols except arc Rs6, which intersects three symbols.

Those arcs which lie exactly midway between two nominal arcs Rs are represented by broken lines. The reference characters of these arcs run from Rg1 to Rg8. If for a received symbol S which differs from the predetermined symbol alphabet Sm,n due to interference or because control loops are not locked, a different radius R is measured, then the circular arcs represented by broken lines correspond to limit lines which include the most probable nominal radius Rs. Therefore, the radii of these range limits are herein referred to as limit radii Rg. The definition of the middle between two nominal arcs as a limit radius is simple, but not mandatory. For

instance, the respective limit radii may be shifted from the middle in either direction, as indicated by the dash-dot arcs in Fig. 4. The limit radius Rg1 , for example, increases the detection range around the nominal radius Rs1. If the limit radius Rg2 is replaced by the two limit radii Rs2+ and Rs3-, then an annulus (shown hatched) is obtained between these radii in which a decision on the most probable nominal radius is suppressed. The limit radii Rs3- and Rs3+ narrow down the evaluation range for the nominal radius Rs3, whereby the number of wrong decisions is reduced. Between the third and fourth nominal radii Rs3 and Rs4, another narrow masked-out region, which lies between the limit radius Rs3+ and the midway limit radius Rg3, is shown hatched by way of example.

The nominal radii Rs6 and Rs7 differ only little. It may be appropriate to exclude these uncertain regions from the decision as to which is the most probable nominal radius. This region could be defined by the limit radii Rg5 and Rg7, for example.

If the selection of the most probable nominal radius Rsi is made not only via the radius R but also via the angle α, the range limits will no longer be purely circular arcs but will deform more or less. In the vicinity of a symbol to be expected, Sm,n, the regions will increase in size, and if the possible symbol Sm,n is relatively far away in terms of angular distance, the regions will decrease correspondingly.

As an example, Fig. 4 illustrates the formation of an auxiliary symbol Sh from a received signal s or a preliminary symbol S. This symbol S has the radius component R and the angle component α. The preliminary symbol S lies within the range limits Rg5 and Rg6. Therefore, the most probable nominal radius Rsi for the symbol S is the nominal radius Rs6. The position of the auxiliary symbol Sh is defined by the most probable nominal radius Rs6 and the existing angle component α. The polar coordinates Rs6 and α of the auxiliary symbol Sh can be converted into components of the quadrature signal pair I, Q with the aid of the Cartesian grid or via a suitable transformation. The auxiliary symbol Sh, except for the angle component α, thus corresponds to the symbols S1,7, S5,5, or S7.1, which all lie on the same nominal radius Rs6. This is an essential difference from conventional symbol decision devices, which make essentially a distance decision. In such distance decision devices, the preliminary symbol S would have been assigned to the symbol S7,3 or possibly to the symbol S5,3, which are both nearer than the symbols on the nominal arc Rs6.

Fig. 5 shows schematically in block-diagram form one embodiment of a demodulator 1 according to the invention for receiving digital signals s, which incorporates an auxiliary-symbol generator. A signal source 2, for instance a tuner, provides the digital signal s in a band-limited intermediate-frequency position. There it is sampled and digitized by means of an A/D converter 3. The fixed digitization clock td is provided by a clock

generator 4. As a rule, the digitization clock td is identical with the system clock for the entire demodulator 1. The output of A/D converter 3 is a digitized signal sd, which is fed to a bandpass filter 5, which removes DC components and undesired harmonics. Connected to bandpass filter 5 is a quadrature mixer 6, which downconverts the digital signal s or the digitized signal sd to baseband and splits it up into the two quadrature signal components I, Q. For the frequency conversion, quadrature mixer 6 is supplied with two carriers 90 degrees apart in phase from a local oscillator 7 whose frequency and phase are controlled by a carrier controller 8. Before the quadrature signal pair I, Q is further processed, undesired harmonics are removed by means of a low-pass filter 9. The filtered quadrature signal pair I, Q is fed to a symbol sampling device 10, which is controlled by a sampling controller 11, which defines the symbol sampling instants ts. In the normal operating state, the symbol sampling instants ts are determined by the symbol rate 1/T and the exact phase position of the received digital signal s. Since the digitization rate td is not synchronized with the symbol rate 1/T, in sampling device 10 a temporal interpolation between the real sample values is performed at the symbol rate or an integral multiple thereof, see also Fig. 3.

The output of sampling device 10 is filtered by means of a low-pass filter 35 with a Nyquist characteristic, and then applied to a gain-controlled amplifier 12 with feedback. Amplifier 12 is controlled by a gain controller 13. The gain control is necessary to ensure that the

dynamic range of a symbol decision stage 15 is properly utilized. After an equalizer 14, the two components of the quadrature signal pair I, Q are free of distortion and are available as a preliminary symbol S. From the preliminary symbols S, the symbol decision stage 15 forms decisions symbols Se, which are applied directly or through a multiplexer 18 to further digital signal processing devices 16 and to the decision-feedback controllers 8, 11, 13, 14 in demodulator 1. Since an angle component α cannot be dispensed with in the control process performed in carrier controller 8, the latter, unlike the other controllers 11, 13, 14, is not connected to multiplexer 18.

The generation of the auxiliary symbol Sh takes place in an auxiliary-symbol decision facility 17. The input stage of auxiliary-symbol decision facility 17 is a resolver 20 which converts the sampled quadrature signal pair I, Q or the preliminary symbol S into polar coordinates R, α. A radius decision stage 21 then determines the most probable nominal radius Rsi from the polar coordinates R, α, particularly from the radius component R. The limit radii Rg and the associated nominal radii Rs are advantageously retrieved from a table 22. The result of the radius decision is the most probable radius Rsi, which, in together with the angle component α, is fed to an inverse resolver 23, which forms the quadrature components Ih, Qh from the polar coordinates Rsi, α. The quadrature components are applied to one input of multiplexer 18, whose other input is fed with the quadrature components of the decision symbol Se. Thus, in

the adjustment phase, controllers 11, 13 and equalizer 14 can be fed with the relatively reliable auxiliary symbol Sh instead of the uncertain decision symbol Se.

The block diagram of Fig. 6 shows another embodiment of a demodulator 1 according to the invention for receiving digital signals s, which incorporates an auxiliary-symbol generator 17 as in Fig. 5. As an alternative to the sampling and digitization with a fixed digitization clock td according to Fig. 5, demodulator 1 is supplied with a frequency- and phase-controlled sampling and digitization clock td′ from a controlled oscillator 4 . A controller 40 synchronizes the digitization rate td′ with the symbol sampling instant t/T or a multiple thereof, see also Fig. 2. The subsequent interpolation in the sampling device 10 of Fig. 5 can thus be dispensed with. Furthermore, even the sampling device 10 itself may be omitted as a separate functional unit, since its function is automatically taken over by equalizer 14, which operates at the symbol rate 1/T. The low-pass filter 9 after the quadrature mixer 6 is no longer necessary, either. Its limiting action is provided by the low-pass filter 35 with the Nyquist characteristic.

To control the controller 40, its control inputs are fed with the preliminary symbol S and, at start-up, the auxiliary symbol Sh. When the resulting digitization rate td′ is in sufficiently exact synchronism with the symbol rate 1/T, switchover from the auxiliary symbol Sh to the decision symbol Se is effected by means of multiplexer 18 as in the case of controllers 13 and 14.

Except for the differences described, the embodiment of Fig. 6 is identical to the embodiment of Fig. 5. Therefore, corresponding functional units are designated by like reference characters in both block diagrams, so that they need not be explained again.

The interface 3 for the digitization in Figs. 5 and 6 may also the quadrature mixer 6, for instance if the intermediate frequency after the signal source 2 is too high. The function and generation of the auxiliary symbol Sh are not directly affected thereby. Because of the partially analog signal paths, however, errors and asymmetries may creep in, particularly into the quadrature components I, Q, which can hardly be eliminated by equalizer 14 and thus increase the uncertainty in the symbol recognition.